Computation of the Resonant Frequency of Electrically Thin and Thick Rectangular Microstrip Antennas with the Use of Fuzzy Inference Systems

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ABSTRACT: A new method for calculating the resonant frequency of electrically thin and thick rectangular microstrip antennas, based on the fuzzy inference systems, is presented. The optimum design parameters of the fuzzy inference systems are determined by using the classical, modified, and improved tabu search algorithms. The calculated resonant frequency results are in very good agreement with the experimental results reported elsewhere.
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I. INTRODUCTION

Accurate determination of the resonant frequency of rectangular microstrip antennas is important in the design of microstrip antennas because they have narrow bandwidths and can only operate effectively in the vicinity of the resonant frequency. Several methods [1–45] are available to determine the resonant frequency of rectangular patch antennas. These methods have different levels of complexity, require vastly different computational efforts, and can generally be divided into two groups: simple analytical methods and rigorous numerical methods. Simple analytical methods can give a good intuitive explanation of antenna radiation properties. Exact mathematical formulations in rigorous methods involve extensive numerical procedures, resulting in round-off errors, and may also need final experimental adjustments to the theoretical results. They are also time consuming and not easily included in a computer-aided design (CAD) package.

Most of the previous theoretical and experimental work has been carried out with only electrically thin rectangular microstrip antennas, normally on the order of $h/\lambda_d \leq 0.02$, where h is the thickness of dielectric substrate and λ_d is the wavelength in the substrate. Recent interest has developed in radiators etched on electrically thick substrates. The need for theoretical and experimental studies of microstrip antennas with electrically thick substrates is motivated by several major factors. Among these is the fact that microstrip antennas are currently being considered for use in millimeter-wave systems. The substrates proposed for such applications often have

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high relative dielectric constants and, hence, appear electrically thick. The need for greater bandwidth is another reason for studying thick substrate microstrip antennas. Consequently, this problem, particularly the resonant frequency aspect, has received considerable attention. The theoretical resonant frequency values obtained by using the previous methods are also not in very good agreement with the experimental results of both electrically thin and thick rectangular microstrip antennas. For these reasons, in this work a new method based on fuzzy inference systems (FISs) for calculating the resonant frequency of both electrically thin and thick rectangular microstrip antenna elements has been presented. The improved, modified, and classical tabu search algorithms have been applied to find the design parameters of the FISs.

FISs [46–49] are nonlinear systems capable of inferring complex nonlinear relationships between input and output variables. The nonlinearity property is particularly important when the underlying physical mechanism to be modeled is inherently nonlinear. The system can "learn" the nonlinear mapping by being presented a sequence of input signal and desired response pairs, which are used in conjunction with an optimization algorithm to determine the values of the system parameters. The system produced by the learning algorithm should be able to generalize to certain regions of the multidimensional space where no training data were given. Even if the process to be modeled is nonstationary, the system can be updated to reflect the changing statistics of the process. Unlike conventional stochastic models used to model such processes, FISs do not make any assumptions regarding the structure of the process, nor do they invoke any kind of probabilistic distribution model, i.e., they belong to the general family of model-free, data driven, nonparametric methods. Because of the fascinating features of FISs, many applications can be found in the literature. They include those in automatic control, data classification, decision analysis, expert systems, and computer vision. FISs in this article are used to model the relationship between the parameters of the microstrip antenna and the measured resonant frequency results.

A number of learning algorithms [47–49] used in FISs are available in the literature. These learning algorithms can be used to construct FISs with different properties and characteristics. Some of these algorithms are data intensive, some are aimed at computational simplicity, some are recursive (thus giving the FISs an adaptive nature), some are offline, and some are application specific. In the design of FISs, it is very important to determine the types and parameters of membership functions, and the consequent parameters, necessary to adequately represent a given system. Given an initial set of membership functions, one wants to select the best possible subset of membership functions for an effective representation. The tabu search algorithms used in this paper enable us to obtain the best possible parameters of FIS.

The classical tabu search meta-strategy [50–53] has been shown to be an effective and efficient scheme for combinatorial optimization that combines a hill-climbing search strategy based on a set of elementary moves and heuristics to avoid stops at suboptimal points and the occurrence of cycles. It has been successfully applied to obtain optimal or suboptimal solutions to problems such as scheduling, timetabling, traveling salesperson, and layout optimization. In our previous work [54], we successfully introduced the modified tabu search algorithm (MTSA) to compute the resonant frequencies of triangular microstrip antennas. In [54], first, a model for the effective side length expression of triangular microstrip antenna was chosen, then the unknown coefficient values of the expression were optimized by the MTSA. The number of neighbors of each variable was fixed to the two values, and the tabu restrictions based on recency and frequency memories were used. The disadvantages of the MTSA are that it has a very limited number of candidate solutions at each iteration and is typically slow to converge. Because of these disadvantages, in this study the MTSA is improved.

The resonant frequency of rectangular microstrip antennas is a function of the dimensions of the patch, the permittivity of the substrate, and its thickness. Principally, the resonant frequency is calculated by using a resonant-length transmission line or cavity model, together with equations for the effective dielectric constant and edge extension from the literature. The FIS proposed here requires neither a formula nor the calculation of the effective dielectric constant and the edge extension. The proposed system only requires the dimensions of the patch, the permittivity of the substrate, and its thickness.

The main aims of this paper are:

- to show the applicability of the FIS to the calculation of resonant frequency for electrically thin and thick rectangular microstrip antennas;

- to improve the tabu search algorithms proposed in the literature;
- to determine optimally the design parameters of the FIS by using the classical tabu search algorithm (CTSA) proposed by Glover [50, 51], the MTSA proposed by Karaboga et al. [54], and the tabu search algorithm improved in this work; and
- to compare the performance of the improved tabu search algorithm (ITSA) with the CTSA and the MTSA.

The theoretical resonant frequency results calculated by using the FIS proposed in this paper are in very good agreement with the experimental results [23, 33, 43, 44]. The model is simple and very useful to antenna engineers for predicting accurately the resonant frequencies of both electrically thin and thick rectangular microstrip antennas. The authors [55–60] also proposed simple methods and formulas for calculating accurately the resonant frequencies of circular and triangular microstrip antennas. These methods and formulas are also very useful for engineering applications and CAD.

II. RESONANT FREQUENCY OF RECTANGULAR MICROSTRIP ANTENNA

Consider a rectangular patch of width W and length L, both comparable to $\lambda_d/2$, over a ground plane with a substrate of thickness h and a relative dielectric constant ε_r, as shown in Figure 1. The resonant frequency f_{mn} of the antenna can be evaluated from

$$f_{mn} = \frac{c}{2(\varepsilon_e)^{1/2}}\left[(m/L_e)^2 + (n/W_e)^2\right]^{1/2} \quad (1)$$

where ε_e is the effective relative dielectric constant for the patch, c is the velocity of electromagnetic waves in free space, m and n take integer values, and L_e and W_e are the effective dimensions. To calculate the resonant frequency of a rectangular patch antenna driven at its fundamental TM_{10} mode, eq. (1) is written as

$$f_{10} = \frac{c}{2(\varepsilon_e)^{1/2}L_e} \quad (2)$$

The effective length L_e can be defined as follows:

$$L_e = L + 2\Delta L \quad (3)$$

The effects of the nonuniform medium and the fringing fields at each end of the patch are accounted for by the effective relative dielectric constant, ε_e, and the edge extension, ΔL, being the effective length to which the fields fringe at each end of the patch. The following effective dielectric constant expression proposed by Schneider [61] and edge extension expression proposed by Hammerstad [20] can be used in Eqs. (2)–(3)

$$\varepsilon_e(W) = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 10h/W}} \quad (4)$$

$$\Delta L = 0.412h\frac{[\varepsilon_e(W) + 0.300](W/h + 0.264)}{[\varepsilon_e(W) - 0.258](W/h + 0.813)} \quad (5)$$

The resonant frequency can be also calculated by using the following formula [2]

$$f_{r1} = f_{r0}\frac{\varepsilon_r}{\sqrt{\varepsilon_e(W)\varepsilon_e(L)}}\frac{1}{(1 + \Delta)} \quad (6)$$

$$\Delta = \frac{h}{L}\left[0.882 + \frac{0.164(\varepsilon_r - 1)}{\varepsilon_r^2} + \frac{(\varepsilon_r + 1)}{\varepsilon_r \pi} \times\left(0.758 + \ln\left(\frac{L}{h} + 1.88\right)\right)\right],$$

and

$$f_{r0} = \frac{c}{2L\sqrt{\varepsilon_r}} \quad (7)$$

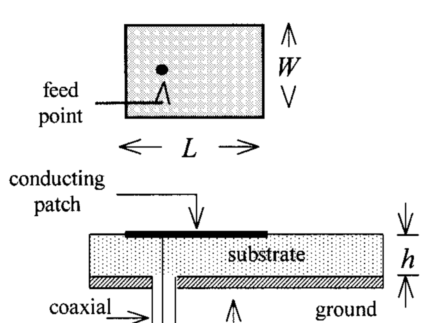

Figure 1. Geometry of rectangular microstrip antenna.

It is clear from eqs. (1)–(7) and all of the formulas proposed in the literature [1–45] that the resonant frequency of a rectangular microstrip antenna is determined by W, L, h, and ε_r.

In this work, the resonant frequency of the rectangular microstrip antennas is calculated by using a new model based on FIS. Only four parameters, W, L, h, and ε_r, are used in calculating the resonant frequency. The new model requires neither a formula given by eqs. (1), (2), and (6) nor the calculations of the edge extension given by eq. (5) and the effective permittivity constant given by eq. (4).

In the following sections, the FISs and the CTSA are described briefly, and the tabu search algorithm improved in this work and the application of FIS to the calculation of the resonant frequency of both electrically thin and thick rectangular microstrip antennas are then explained.

III. FIS

The FIS [47–49] is a popular computing framework based on the concepts of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning. Basically, a FIS is composed of four functional blocks as shown in Figure 2:

a) **Fuzzification** maps the crisp inputs into fuzzy sets, which are subsequently used as inputs to the inference engine. A fuzzy set U is characterized by a membership function (MF) μ: $U \rightarrow \{0,1\}$. The membership functions are labeled by a linguistic term such as "small," "medium," or "large." In the following, the several classes of parameterized functions commonly used to define membership functions are given
   i) Gaussian MFs

$$\text{Gaussian}(x; a, b, c) = \exp\left(-\left(\frac{x-a}{c}\right)^{2b}\right) \quad (8)$$

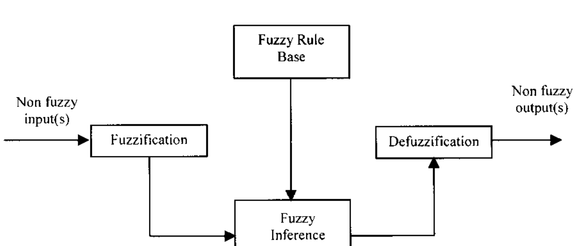

Figure 2. Basic fuzzy inference system.

   ii) Generalized bell MFs

$$\text{Bell}(x; a, b, c) = \frac{1}{1 + \left|\dfrac{x-a}{c}\right|^{2b}} \quad (9)$$

   iii) Trapezoidal MFs

$$\text{Trapezoid}(x; a, b, c) = \begin{cases} 0, & x \geq c + \dfrac{b}{2} + \dfrac{1}{a} \text{ or } x \leq c - \dfrac{b}{2} - \dfrac{1}{a} \\ 1, & x < c + \dfrac{b}{2} \text{ or } x > c - \dfrac{b}{2} \\ a\left(c + \dfrac{b}{2} + \dfrac{1}{a} - x\right), & x > c \\ a\left(x - c + \dfrac{b}{2} + \dfrac{1}{a}\right), & x \leq c \end{cases} \quad (10)$$

   The parameterized membership functions given in eqs. (8)–(10) play an important role in the FISs. In order to obtain a desired MF which minimizes the cost function, the parameter set $\{a, b, c\}$ in eqs. (8)–(10) is optimized by using the ITSA, MTSA, and CTSA.

b) **Fuzzy rule base** is a set of fuzzy rules in the form of if-then clauses. For a multi-input single output case, the tth rule can be expressed by

$$R^t: \text{if } x_1 \text{ is } A_1^t \text{ and } x_2 \text{ is } A_2^t \text{ and} \ldots \text{ and } x_n \text{ is } A_n^t \text{ then } y \text{ is } B^t \quad (11)$$

   where $\mathbf{x} = (x_1, x_2, \ldots, x_n)$ is the input vector, y is the output variable, and A_i^t and B^t are the labels of membership functions associated to the input variable x_i in the rule t and to the output variable y in the rule t, respectively.

c) **Fuzzy inference engine** is a decision-making logic which performs the inference operations on the rules and a given condition to derive a reasonable output or conclusion. Three types of FISs [48], the Mamdani fuzzy model, the Sugeno fuzzy model, and the Tsukamoto fuzzy model, have been widely used in various applications. The differences between these three FISs lie in the consequents of their fuzzy rules, and thus their aggregation and defuzzification procedures differ accordingly. In this work, the Sugeno fuzzy model was used. In this model, the tth rule can be written as

$$R^t: \text{ if } x_1 \text{ is } A_1^t \text{ and } x_2 \text{ is } A_2^t \text{ and} \ldots \text{ and } x_n \text{ is } A_n^t \text{ then } y_t \text{ is } \xi_{0t} + \xi_{1t}x_1 + \xi_{2t}x_2 + \ldots + \xi_{nt}x_n \quad (12)$$

where ξ_{it} is the consequent parameters of the Sugeno model.

d) **Defuzzification** transforms the fuzzy results of the inference into a crisp output. The most commonly used defuzzification strategy is the centroid of area, which is defined as

$$\text{output} = \frac{\int_Y y\mu_B(y)\,dy}{\int_Y \mu_B(y)} \quad (13)$$

where $\mu_B(y)$ is the aggregated output MF. Other defuzzification strategies arise for specific applications, which includes bisector of area, mean of maximum, largest of maximum, and smallest of maximum, and so on. These defuzzification strategies are shown in Figure 3. These strategies are computation intensive, and there is no rigorous way to analyze them except through experimental-based works.

In this work, the optimum design parameters of FIS explained above are determined by using the ITSA, MTSA, and CTSA.

IV. CTSA

The tabu search [50–53] is a meta-heuristic algorithm which uses memory to guide an iterative

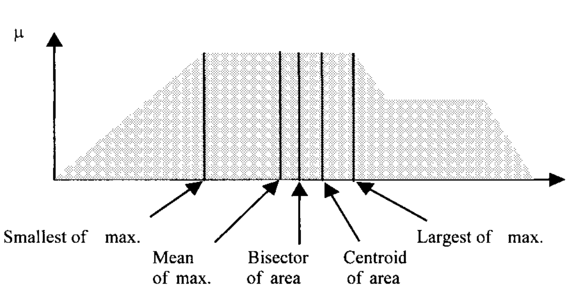

Figure 3. Various defuzzification strategies.

1) $j = 0$; initialize s_{now}; $s_{\text{best}} = s_{\text{now}}$; tabu$(j) = \varnothing$.
2) Construct a list of candidate moves from the neighborhood of s_{now}. Evaluate each candidate move.
3) If a move is in tabu(j), but leads to a highly desired solution, perform the move, update s_{now}, and go to step 4. Otherwise, select the non-tabu move with the highest evaluation. Perform the move, and update s_{now}.
4) If s_{now} is better than s_{best}, update s_{best}.
5) If stopping criteria are satisfied, terminate with s_{best}. Otherwise, $j = j + 1$; update tabu(j); go to step 2.

Figure 4. Main structure of classical tabu search algorithm.

search. At each iteration of the search, a neighborhood is examined to construct new solutions. These solutions are compared against the memory structure (i.e., tabu list) to prevent cycling. The best new solution which is not tabu list is selected and the system moves to that new solution. This process continues until a predetermined termination criterion is reached, e.g., every move is tabu or a maximum number of iterations has been reached. The main structure of the basic tabu search is given in Figure 4. In the figure, s_{now}, s_{best}, j, and tabu(j) represent, respectively, the solution at the current iteration, the best solution found so far, the current iteration counter, and the set of tabu moves at iteration j.

V. ITSA

The CTSA uses a solution vector consisting of a string of bits. Thus, in solving a numerical problem, the transformation from binary to real numbers should be used. This process has two major disadvantages. The first disadvantage is that the process yields a large number of neighbors (e.g., too many evaluations) when the word chosen is very long. The second disadvantage is the difficulty with neighborhood processing. This difficulty is that while a neighbor of the solution vector (e.g., a string of bits) is obtained, the changing of the most significant bit does not produce a number near the present variable. So, this is not reasonable regarding the neighborhood. In order to overcome these difficulties, the MTSA and ITSA have been proposed in our previous work [54] and in this work, respectively.

A real-valued solution vector is used by the ITSA and MTSA; thus, a new neighbor production mechanism is constructed. In this mechanism, the neighbors are chosen adaptively, adding an adaptive coefficient at each iteration. Due to the diversification principle, the coefficient is large at early iterations; therefore, the neighbors are chosen too far from the present solution. This neighbor production mechanism enables us to find the most promising region of the search space. After some iterations, the coefficient is getting smaller; thus, the intensive searching at the most promising region can be done.

The difference between the ITSA and the MTSA is the number of neighbors produced at each iteration. While the MTSA uses the fixed number of neighbors for each variable in the solution vector, the ITSA obtains the number of neighbors, adaptively. At each iteration, the average of the results obtained from the neighbors of each variable is used in the ITSA for calculating the number of neighbors at the next iteration. The neighbors of a present solution of the ITSA are created by the following procedure.

At the first iteration, each variable on the solution has two neighbors. After all neighbors are evaluated, the average of evaluation values is calculated for each variable. If $\mathbf{s}_j = (s_{j,1}, s_{j,2}, \ldots, s_{j,n})$ is the solution vector at the jth iteration, the number of neighbors, $\text{NumOf\_N}(s_{j+1,k})$, at the next iteration is determined by the following formula developed in this work,

$$\text{NumOf\_N}(s_{j+1,k}) = \text{NumOf\_N}(s_{j,k}) \times \left(2 \frac{A(k) - \min(A)}{\max(A) - \min(A)} \right) \tag{14}$$

where $A(k)$ is the average value of evaluations of the kth variable's neighbors and $\max(A)$ and $\min(A)$ are the maximum and the minimum averages of all variables at the jth iteration, respectively. The value of eq. (14) is rounded towards the nearest integer value. It is clear from Eq. (14) that the variables having good averages get more neighbors at the next iteration, otherwise the number of neighbors becomes smaller.

At the jth iteration, the ith neighbor N of the kth variable is produced by the following expression proposed in this work,

$$N(s_{j,k}) = N(s_{j-1,k}) + \frac{i}{2}(-1)^i \Delta(j) \tag{15}$$

with

$$\Delta(j) = \frac{\lambda}{j} \left[\frac{\text{LatestImprovementIteration}}{j + \text{LatestImprovementIteration}} \right]^{\alpha} \tag{16}$$

where λ determines the initial magnitude of $\Delta(j)$, and α controls the change of $\Delta(j)$. The index, j, in $\Delta(j)$ represents the iteration number. The suitable values for the parameters λ and α in eq. (16) are determined by experience on the tabu search. LatestImprovementIteration in Eq. (16) is the iteration number at which the latest improvement was obtained.

Later, in order to prevent from any excess of the boundary values of the kth variable, every neighbor is inserted into a search space by using

$$N(s_{j,k}) = s_{k_{\min}} + \text{Remain}\left(N(s_{j,k}), s_{k_{\max}} - s_{k_{\min}}\right) \tag{17a}$$

with

$$\text{Remain}(x, y) = x \bmod y \tag{17b}$$

where $s_{k_{\min}}$ and $s_{k_{\max}}$ are the minimum and maximum boundary values of the kth variable, respectively. The "remain function" in eq. (17b) keeps the elements of solution within the desired ranges.

At initialization, the goal is to make a coarse examination of the solution space, known as "diversification," but as the candidate locations are identified the search is more focused to produce local optimal solutions in a process of "intensification." At the early iterations, $\Delta(j)$ is too high, and owing to the remain function, it seems that the search direction looks like a random search as in the diversification principle. While the number of iterations increases, $\Delta(j)$ decreases exponentially and the neighbors produced become very near to the solution.

In order to describe clearly the ITSA proposed in this work, the main structure of this algorithm is given in Figure 5.

A solution vector $\mathbf{s}$ consists of real and integer values and is given by

$$\mathbf{s} = [k_{11} a_{11} b_{11} c_{11} k_{12} a_{12} b_{12} c_{12} \ldots k_{1m} a_{1m} b_{1m} c_{1m} \; \xi_{10}\, \xi_{11}\, \xi_{12} \cdots \xi_{1m} \cdots \; k_{n1} a_{n1} b_{n1} c_{n1} k_{n2} a_{n2} b_{n2} c_{n2} \ldots k_{nm} a_{nm} b_{nm} c_{nm} \; \xi_{n0}\, \xi_{n1}\, \xi_{n2} \cdots \xi_{nm}] \tag{18}$$

```
{initialization}
N := Number of variables (e.g. length of solution
     vector)
Best := Infinitive;
tabu_List[1..100] := NULL;
NumNeigh[1..N] := 5;
{all averages set to 1}
A[1..N] := 1;
S_0 = random(N);
for j := 2 to Last_Iteration
begin
    For k := 1 to N
    begin
    {calculating number of neighbors for each variable
    using eqs. (14-17)}
        For i := 1 to NumNeigh[k]
        begin
            {producing neighbors}
            C_{k,i} = S_k + 0.5*i*(-1)^{i}*Δ(j)
            {projection to search space}
            C_{k,i} = S_{k min} + Remain(C_{k,i}, (S_{k max} -
                      S_{k min}))
            If C_{k,i} not in tabu_list then
              E_{k,i} = evaluate(C_{k,i})
            End;
        End;
        A(k) = Average(E_k)
    End;
    E_min := minimum(E)
    {update the best solution}
    If E_min < Best then Best := E_min;
    {update tabu list}
    Add(tabu_List, parameters of C_min)
End;
```

Figure 5. Main structure of improved tabu search algorithm.

where k_{ij}, a_{ij}, b_{ij}, and c_{ij} are the type, the position, the slope, and the flatness parameters of input membership functions, respectively. The subscripts n and m in eq. (18) are the number of rules and the number of inputs, respectively. The rule constructed by the input membership function and consequent parameters can be written as

$$R_i = [M_{i1} M_{i2} \dots M_{im}\, \xi_{i0}\, \xi_{i1}\, \xi_{i2} \dots \xi_{im}] \quad (19)$$

where M_{ij} is the jth input membership function for the ith rule, and is a function of k_{ij}, a_{ij}, b_{ij}, and c_{ij}.

While the MTSA uses the tabu restrictions based on the recency and frequency memories, the ITSA uses the tabu restriction strategy based on the type of list form. Each list element in the ITSA consists of the input membership function parameters M_{ij}. Therefore, four parameters, k_{ij}, a_{ij}, b_{ij}, and c_{ij}, are stored in a list element. The structure of the list used is LIFO (last in first out). If a membership function exists in the tabu list, this function is rejected and the membership function which is not in the tabu list is reproduced. If all of the membership functions produced are listed in the tabu list, the aspiration criterion is used. The aspiration criterion used in this work is that the last element in the tabu list is extracted from the list.

VI. APPLICATION OF FIS TO THE CALCULATION OF THE RESONANT FREQUENCY

The proposed technique involves training a FIS to calculate the resonant frequency (RF) when the values of W, L, h, and ε_r are given. Figure 6 shows the FIS model used in computation of the RF. Training the FIS by the ITSA, MTSA, and CTSA to compute the RF involves presenting them sequentially with different (W, L, h, ε_r) sets and corresponding measured values f_{ME}. Differences between the target output f_{ME} and the actual output RF of the FIS are used to determine optimally the types and parameters of the membership functions and the consequent parameters. This optimum determination is made by using the ITSA, MTSA, and CTSA. The optimization is carried out after the presentation of each set (W, L, h, ε_r) until the calculation accuracy of the FIS is deemed satisfactory according to the root-mean-square error between the target output f_{ME} and the actual output RF for all the training sets that fall below a given threshold or the maximum allowable number of iteration is reached.

The training and test data sets used in this paper have been obtained from previous experimental works [23, 33, 43, 44] and are given in Table I. Nine data sets (marked with superscript b) are used for testing, and the remaining 37 data

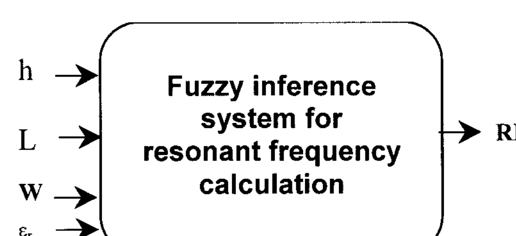

Figure 6. Fuzzy model for resonant frequency computation.

TABLE I. Comparison of Measured and Calculated Resonant Frequencies of Electrically Thin and Thick Rectangular Microstrip Antennas

W (cm)	L (cm)	h (cm)	ε_r	$(h/\lambda_d)\times 10^2$	f_{ME} [23, 33, 43, 44] Measured	Present FIS Models f_{ITSA}	f_{MTSA}	f_{CTSA}	f_{HO} [19]	f_{HA} [20]	f_{CA} [23]	f_{BA} [1]	f_{JA} [2]	f_{SE} [30]	f_{GA} [34]	f_{CH} [35]	f_{GU} [41]	f_{KA1} [44]	f_{KA2} [44]	f_{ANN} [45]
5.700	3.800	0.3175	2.33	3.7317	2310[a]	2310.0	2310.0	2310.0	2586	2381	2373	2452	2296	2458	2389	2377	2323	628	786	2309
4.550	3.050	0.3175	2.33	4.6687	2890[a]	2890.0	2890.0	2890.0	3222	2911	2893	3013	2795	3042	2915	2908	2831	963	1219	2890
2.950	1.950	0.3175	2.33	6.8496	4240[a]	4240.1	4240.1	4240.2	5039	4327	4239	4529	4108	4681	4296	4331	4191	2294	2983	4224
1.950	1.300	0.3175	2.33	9.4344	5840[a]	5839.5	5839.7	5840.0	7559	6085	5928	6448	5700	6918	5965	6089	5919	5032	6712	5841
1.700	1.100	0.3175	2.33	10.9852	6800[a]	6800.7[b]	6800.7[b]	6799.8[b]	8933	6958	6806	7405	6467	8109	6761	6909	6798	6955	9375	6832
1.400	0.900	0.3175	2.33	12.4392	7700[a]	7698.7	7698.4	7699.1	10919	8137	7956	8711	7482	9836	7820	7889	7528	10261	14005	7704
1.200	0.800	0.3175	2.33	13.3600	8270[a]	8271.7	8272.1	8271.3	12284	8905	8986	9579	8132	11054	8508	8402	8254	12894	17725	8270
1.050	0.700	0.3175	2.33	14.7655	9140[a]	9139.2	9139.1	9139.3	14038	9831	11330	10621	8894	12588	9306	8709	9141	16706	23151	9146
1.700	1.100	0.9525	2.33	22.9236	4730[a]	4730.0	4730.0	4730.0	8933	5101	1094597	5614	4320	7958	4525	5109	4922	19581	28126	4728
1.700	1.100	0.1524	2.33	6.1026	7870[a]	7870.0	7869.9	7869.7	8933	7829	7694	8154	7463	8341	7795	7825	7585	3494	4500	7839
4.100	4.140	0.1524	2.50	1.7896	2228[c]	2228.0	2228.0	2228.0	2292	2209	2232	2259	2175	2248	2245	2222	2197	281	266	2226
6.858	4.140	0.1524	2.50	1.7671	2200[c]	2200.0[b]	2200.0[b]	2200.0[b]	2292	2208	2204	2241	2158	2228	2221	2206	2180	281	266	2190
10.80	4.140	0.1524	2.50	1.7518	2181[c]	2181.0	2181.0	2181.0	2292	2208	2184	2230	2148	2216	2204	2210	2168	281	266	2181
0.850	1.290	0.0170	2.22	0.6535	7740	7740.1	7740.1	7740.0	7804	7697	7750	7791	7635	7737	7763	7720	7717	295	412	7736
0.790	1.185	0.0170	2.22	0.7134	8450	8449.7[b]	8449.6[b]	8449.6[b]	8496	8369	8431	8478	8298	8417	8446	8396	8389	349	488	8414
2.000	2.500	0.0790	2.22	1.5577	3970	3970.1	3970.1	3970.2	4027	3898	3949	3983	3838	3951	3950	3917	3887	358	510	3966
1.063	1.183	0.0790	2.55	3.2505	7730	7730.3	7730.4	7730.7	7940	7442	7605	7733	7322	7763	7639	7551	7376	1775	1610	7725
0.910	1.000	0.1270	10.2	6.2193	4600	4600.0	4600.0	4600.0	4697	4254	4407	4641	4455	4979	4729	4614	4430	14548	113	4600
1.720	1.860	0.1570	2.33	4.0421	5060	5060.0	5060.4	5061.9	5283	4865	4989	5070	4741	5101	4958	4924	4797	1294	1621	5058
1.810	1.960	0.1570	2.33	3.8384	4805	4804.9[b]	4804.4[b]	4802.9[b]	5014	4635	4749	4824	4520	4846	4724	4688	4573	1169	1460	4828
1.270	1.350	0.1630	2.55	5.6917	6560	6559.8	6560.0	6560.5	6958	6220	6421	6566	6067	6729	6382	6357	6114	2719	2550	6542
1.500	1.621	0.1630	2.55	4.8587	5600	5600.1	5600.2	5600.3	5795	5270	5424	5535	5158	5625	5414	5374	5194	1907	1769	5581
1.337	1.412	0.2000	2.55	6.6004	6200	6200.0[b]	6199.2[b]	6197.0[b]	6653	5845	6053	6201	5682	6413	5987	5988	5735	3019	2860	6189
1.120	1.200	0.2420	2.55	9.0814	7050	7050.1	7050.6	7050.5	7828	6566	6867	7052	6320	7504	6682	6769	6433	4942	4792	7023
1.403	1.485	0.2520	2.55	7.7800	5800	5800.5	5801.1	5801.9	6325	5435	5653	5801	5259	6078	5552	5586	5326	3399	3259	5801
1.530	1.630	0.3000	2.50	8.3326	5270	5269.6	5269.0	5268.5	5820	4943	5155	5287	4762	5572	5030	5081	4842	3281	3383	5266
0.905	1.018	0.3000	2.50	12.6333	7990	7990.2	7990.6	7991.8	9319	7334	7813	7981	6917	8885	7339	7570	6822	8153	8674	7967
1.170	1.280	0.3000	2.50	10.3881	6570	6569.6	6569.0	6570.0	7412	6070	6390	6550	5794	7076	6135	6264	5951	5236	5486	6554
1.375	1.580	0.4760	2.55	12.9219	5100	5100.0[b]	5098.3[b]	5095.1[b]	5945	4667	4993	5092	4407	5693	4678	4830	4338	5457	5437	5157
0.776	1.080	0.3300	2.55	14.0525	8000	7999.5	7998.7	7997.0	8698	6845	7546	7519	6464	8447	6889	7160	6367	8089	8067	7990
0.790	1.255	0.4000	2.55	15.1895	7134	7134.9	7136.1	7137.9	7485	5870	6601	6484	5525	7342	5904	6179	5452	7241	7242	7107
0.987	1.450	0.4500	2.55	14.5395	6070	6069.5	6066.6	6068.8	6478	5092	5660	5606	4803	6317	5125	5341	4735	6113	6103	6067
1.000	1.520	0.4760	2.55	14.7462	5820	5821.6[b]	5829.2[b]	5838.2[b]	6180	4855	5423	5352	4576	6042	4886	5100	4513	5881	5875	5847
0.814	1.440	0.4760	2.55	16.1650	6380	6378.9	6377.0	6369.3	6523	5101	5823	5660	4784	6453	5122	5396	4729	6529	6546	6392
0.790	1.620	0.5500	2.55	17.5363	5990	5989.7	5987.9	5986.5	5798	4539	5264	5063	4239	5804	4550	4830	4196	5950	5976	5950
1.200	1.970	0.6260	2.55	15.5278	4660	4660.1	4660.4	4660.8	4768	3746	4227	4141	3526	4689	3770	3949	3479	4600	4600	4632
0.783	2.300	0.8540	2.55	20.9105	4600	4599.9	4600.0	4600.2	4084	3201	3824	3615	2938	4209	3168	3446	2921	4556	4603	4602
1.256	2.756	0.9520	2.55	18.1413	3580	3579.5[b]	3579.4[b]	3579.5[b]	3408	2668	3115	2983	2485	3430	2670	2845	2461	3554	3574	3510
0.974	2.620	0.9520	2.55	20.1683	3980	3978.0	3975.5	3974.5	3585	2808	3335	3162	2590	3668	2790	3015	2572	3920	3955	3954
1.020	2.640	0.9520	2.55	19.7629	3900	3901.7	3903.8	3904.7	3558	2785	3299	3133	2573	3629	2771	2987	2555	3863	3895	3882
0.883	2.676	1.0000	2.55	21.1852	3980	3981.2	3981.7	3982.0	3510	2753	3294	3112	2522	3626	2721	2966	2509	3940	3982	3978
0.777	2.835	1.1000	2.55	22.8353	3900	3899.0	3899.0	3898.6	3313	2608	3147	2964	2364	3473	2554	2823	2356	3852	3903	3982
0.920	3.130	1.2000	2.55	22.1646	3470	3471.2	3470.8	3471.0	3001	2358	2838	2675	2146	3129	2317	2549	2137	3450	3493	3460
1.030	3.380	1.2810	2.55	21.8197	3200	3200.7[b]	3200.3[b]	3200.3[b]	2779	2183	2623	2474	1992	2889	2151	2357	1983	3160	3197	3187
1.265	3.500	1.2810	2.55	20.3196	2980	2980.6	2980.4	2980.2	2684	2102	2502	2370	1936	2752	2086	2259	1924	2954	2982	2963
1.080	3.400	1.2810	2.55	21.4787	3150	3148.1	3149.0	3149.0	2763	2168	2600	2453	1982	2863	2139	2338	1972	3125	3160	3141

[a] These frequencies measured by Chang et al. [33].
[b] Shows the test results. Resonant frequencies are in MHz.
[c] These frequencies measured by Carver [23], the remainder measured by Kara [43, 44].

sets are used for training the FISs. In microstrip antenna designs, the most important parameter is the electrical thickness h/λ_d of the antenna. The electrical thickness values are given in the fifth column of Table I. It is clear from Table I that the range of electrical thickness h/λ_d is very wide for microstrip antennas. As can be also seen from Table I that nine different electrical thicknesses, which are not close to each other, are chosen to test the performance of FISs. These testing sets are also the same as those used for the artificial neural networks [45].

The parameters of the learning algorithms are: *for the ITSA, MTSA, and CTSA*, the number of iterations is fixed to 2000 in the training process, the number of membership functions for the input variables (W, L, h, and ε_r) are 3, 3, 3, and 2, respectively, the number of rules is then 54 [$3 \times 3 \times 3 \times 2 = 54$], three types of membership functions, gaussian, generalized bell, and trapezoidal, are used, and the values of n and m in eq. (18) are 54 and 4, respectively; *for the ITSA and MTSA*, 1134 [$54(4 + 4 + 4 + 4 + 5) = 1134$] parameters are optimized, and the values taken for λ and α in eq. (16) are 100,000 and 2, respectively; *for the ITSA*, the size of the tabu list is fixed to 100; *for the CTSA and MTSA*, the tabu restrictions based on the recency and frequency memories are used, and the recency and frequency factors are 1.5 and 2, respectively; *for the CTSA*, k_{ij} is expressed by 2 bits, each of a_{ij}, b_{ij}, c_{ij}, and ξ_{ij} are represented by 4 bits, and the solution vector consists of 4104 [$54(14 + 14 + 14 + 14 + 20) = 4104$] bits.

The computer program based on the FIS proposed here is written in C. The program begins by asking for the four parameters, W, L, h, and ε_r. The resonant frequency is then calculated directly by the FIS (The program source code for the FIS proposed in this paper can be obtained from the authors either by mail or electronic mail.)

VII. RESULTS AND CONCLUSIONS

In order to determine the most appropriate suggestion given in the literature, we compared our computed values of resonant frequencies for electrically thin and thick rectangular microstrip patch antennas with the theoretical and experimental results reported by other scientists, which are all given in Table I. The entries for f_{ME}, f_{ITSA}, f_{MTSA}, f_{CTSA}, f_{HO}, f_{HA}, f_{CA}, f_{BA}, f_{JA}, f_{SE}, f_{GA}, f_{CH}, f_{GU}, f_{KA1}, f_{KA2}, and f_{ANN} represent, respectively, the values measured [23, 33, 43, 44], calculated by the FIS with the use of the ITSA, MTSA, CTSA, by Howell [19], by Hammerstad [20], by Carver [23], by Bahl and Bhartia [1], by James et al. [2], by Sengupta [30], by Garg and Long [34], by Chew and Liu [35], by Güney [41], by using the curve-fitting formula proposed by Kara [44], by using the modified cavity model [44], and by using the artificial neural networks [45]. The results of Carver [23] are obtained by using a program called MSAnt which was written by Pozar [6]. The total absolute errors (absolute error = |theoretical result−experimental result|) for every suggestion in Table I are also listed in Table II.

It can be clearly seen from Tables I and II that the previous methods give comparable results—some cases are in very good agreement with measurements, and others are far off. The results of the FIS proposed in this work are superior to those predicted by other scientists and are also better than those calculated by using the artificial neural networks proposed in our previous work [45]. The very good agreement between the measured values and our computed resonant frequency values supports the validity of the present FIS.

From the results, we can find that the best results are obtained from the FIS trained by the ITSA. The ITSA is a very powerful method that allows us to design highly accurate and parsimonious FISs. It also needs to be emphasized once more that better and more robust results may be obtained from the proposed method if more input data set values are supplied for training.

Since the model presented in this work has high accuracy and requires no complicated mathematical functions, it can be very useful for the development of fast CAD algorithms. This CAD model, capable of accurately predicting the resonant frequency of electrically thin and thick rectangular microstrip antennas, is also very useful to antenna engineers. Using this model with a personal computer, one can calculate accurately the resonant frequency of rectangular patch antennas without possessing any background knowledge of microstrip antennas. The real-time calculation is less than 200 μs after training. Thus, the FIS is very fast after training. Finally, we expect that the FIS models will find wide applications in CAD of antennas and microwave integrated circuits.

TABLE II. Total Absolute Errors between the Measured and Calculated Resonant Frequencies

Methods	Present FIS Models			f_{HO} [19]	f_{HA} [20]	f_{CA} [23]	f_{BA} [1]	f_{JA} [2]	f_{SE} [30]	f_{GA} [34]	f_{CH} [35]	f_{GU} [41]	f_{KA1} [44]	f_{KA2} [44]	f_{ANN} [45]
	f_{ITSA}	f_{MTSA}	f_{CTSA}												
Total absolute deviations from the measured data (MHz)	23.5	50.5	81.6	36059	26908	1104916	19179	32930	23746	23761	19899	31436	108707	126945	751

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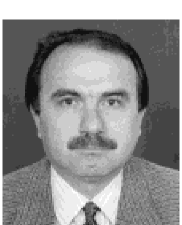

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